Mausam, (1992), 43, 4, 415-420

551.574.12 (267)

Cloud drop spectra in maritime and inland regions

S. K. PAUL and A. G. PILLAI

Indian Institute of Tropical Meteorology, Pune

(*Received 24 July 1991*)

सार—1973, 1974 और 1979 के ग्रीष्म मानसून ऋतुओं के अंत तक अरब महासागर (समुद्रवर्ती) और पुणे (अंतर्देशी) क्षेत्र में विभिन्न स्तरों पर 1–2 कि. मी. मोटे इत्तर वर्षण कपासी मेघों पर मेघ बिंदु आकार स्पेक्ट्रा के माप लिए गए।

अरब महासागर के लिए मेघ बिंदुओं के अधिकतम आकार में सामान्यत: ऊंचाई सहित वृद्धि हुई, जबकि पुणे के लिए ऊँचाई सहित क्रमबद्ध परिवर्तन का पता नहीं चलता है। दोनों स्थानों में बिन्दुओं के कुल सांद्रण में ऊँचाई सहित कमी आई है। समुद्रवर्ती वितरण सभी स्तरों पर द्विबहुलक थे जबकि वे पुणे में सामान्यतया एकबहुलकी थे। तरल जल अंश माध्य परिमाण व्यास, फैलाव के औसत मान और $>50\ \mu m$ व्यास सहित बिंदुओं के सांद्रण कुछ बृहत्तर तथा अंतर्देशी में विद्यमान उनकी तुलना में समुद्री क्षेत्र में कुल सांद्रण थोड़ा सा कम है। $<14\ \mu m$ और $>78\ \mu m$ व्यास बिंदुओं सहित का सांद्रण और अधिकतम आकार समुद्र की अपेक्षा पुणे में बृहत्तर थे। दोनों स्थानों में मेघ बिंदु स्पेक्ट्रा और मेघ संरचना प्राचलों में विभिन्नता पर विचार–विमर्श किया गया।

ABSTRACT. Measurements of cloud drop size spectra on non-precipitating cumulus clouds, 1-2 km thick, were made at different levels over the Arabian Sea (maritime) and over Pune (inland) region during the end of the summer monsoon seasons of 1973, 1974 and 1979.

The maximum size of cloud drops for the Arabian Sea generally increased with height, while that for Pune did not show a systematic change with height. At both the locations, the total concentration of drops decreased with height. The maritime distributions were bimodal at all levels while those over Pune were usually unimodal. The average values of liquid water content, mean volume diameter, dispersion and concentration of drops with diameter $>50\ \mu m$ were a little greater and total concentration a little smaller over the maritime region as compared to those over inland. The concentrations of drops with diameter $<14\ \mu m$ and those $>78\ \mu m$ and the maximum size were greater over Pune than over the sea. The variations in cloud drop spectra and the cloud physical parameters over both the locations are discussed.

Key words — Cloud drop size spectra, Drop concentration, Mean volume diameter, Liquid water content, Dispersion, Bimodal & Unimodal distribution.

1. Introduction

A knowledge of cloud drop size distribution is useful for the study of cloud physics, cloud development and rain formation. Continental clouds have a narrow spectrum and high droplet concentration while maritime clouds have a broad spectrum and low droplet concentration (Squires 1958, Durbin 1959, Jonas and Mason 1974). The cloud droplet spectra in marine cumulus clouds are often bimodal (Durbin 1959, Warner 1969). Usually, a decrease in droplet concentration (Squires 1958, Silvermann and Glass 1973) and an increase in mean volume diameter (Durbin 1959) were reported. An increase in liquid water content, falling towards the cloud top, with height above cloud base in cumulus clouds, were observed (Warner 1955, Silvermann and Glass 1973). The authors present a comparative study of drop size distributions over maritime and inland regions.

2. Measurements

Measurements of drop size spectra were made on non-precipitating cumulus clouds, 1-2 km thick, from a DC-3 aircraft at different levels over the Arabian Sea, about 50 km upwind of Bombay (18° 51′N, 72° 49′E, 11 m msl) and near Pune (18° 32′N, 73° 51′E, 559 m msl) during the end of the summer monsoon seasons of 1973, 1974 and 1979. The observations were made on 13 days over the Arabian Sea and on 16 days over Pune. The number of individual clouds sampled was about twenty at each location. The total number of cloud samples, for which a comparison was made, was 49 over the sea and 50 over Pune. These samples were collected during the course of warm cloud seeding experiments and, as such, limited samples and only average distributions could be obtained at different levels in the absence of single-day vertical profile observations. The experimental area near Pune is about

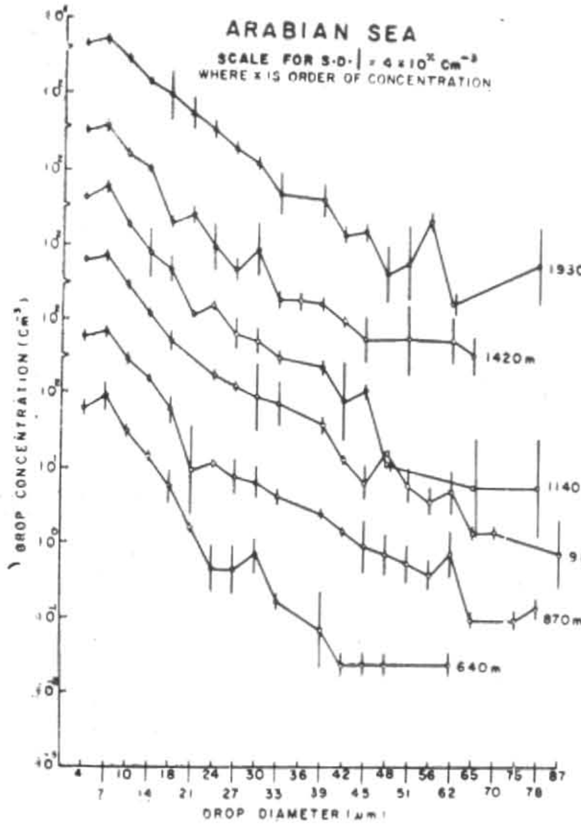

Fig. 1. Cloud drop size spectra over the Arabian Sea at various levels above the sea surface. The ordinate is shifted by one decade for each successive height

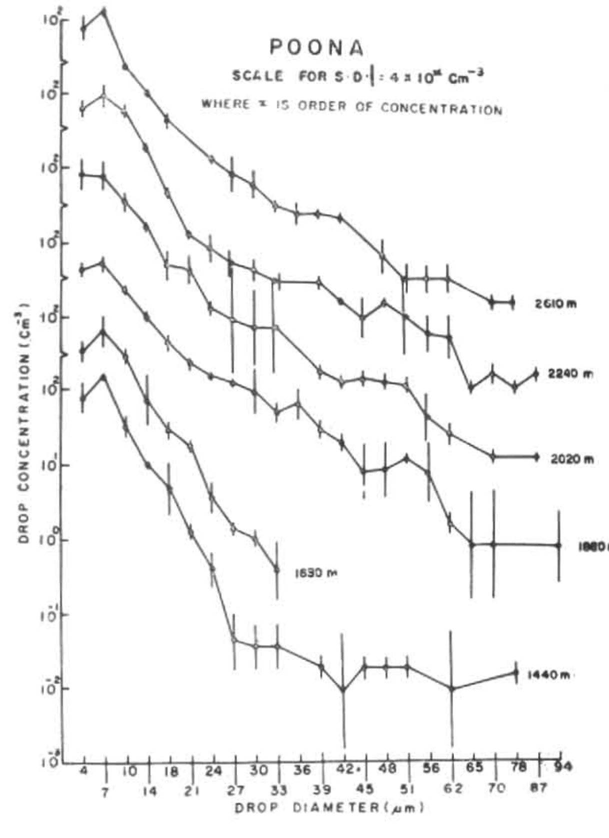

Fig. 2. Cloud drop size spectra over Pune at various levels above mean sea level. The ordinate is shifted by one decade for each successive height

150 km inland of Bombay coast and is situated on the lee side of the Western Ghats. The airmass over the Arabian Sea is purely maritime and that over the Pune region is modified maritime. Over both the locations, winds are mostly westerly to southwesterly in the lower troposphere. Over Pune, the cloud-base height was about 800 to 1100 m (msl), while that over the sea it was usually 300 to 600 m above the sea surface. Microphysical parameters such as maximum size, total cloud drop concentration (N_T), concentration of drops with diameter greater than 50 μm (N_L), liquid water content (LWC), mean volume diameter (MVD) and dispersion of drops were computed. The results in each region are compared. Here, the term 'maximum size' means the maximum drop diameter in each average spectrum at a given level. Also, the term 'dispersion' is defined as the standard deviation of the drop size distribution divided by the arithmetic mean of the same distribution.

A mechanical semi-automatic cloud drop sampler (Srivastava and Kapoor 1960) containing magnesium oxide coated glass slides of size 3.5 cm $\times$ 0.6 cm was used. Each slide was exposed for 14.8 milliseconds in the cloud at an impact speed of 54 m sec^{-1}. The craters were measured using an optical microscope with magnification of 200 X. The exposure was made from a position located about 50 cm away from the aircraft. The volume of cloud sampled during each exposure was about 270 cm^3. True drop diameters were obtained from calibrations made earlier of the ratio of droplet to crater diameter, for a range of cloud drops. For this purpose, cloud drops were collected simultaneously on glass slides with half their area coated with a thin layer (15-20 μm thick) of magnesium oxide and the other half with a very thin film of silicone oil (serving as control). The oil used was of a quality that water did not diffuse into it and so there was no reduction in the size of the cloud droplets. The layer of oil was so thin that the droplets remained on its surface and did not spread. The drops so collected were analysed by an optical microscope and the spectra evaluated. The period between the sampling and analysis varied from 30 minutes to 1 hour. The craters (in the oxide film) with mean diameters of 11.5, 34.5, 58.5, 84.8, 112.9, 149.1 and 241.2 μm correspond to cloud drops (in the oil film) of mean diameters 5.7, 16.1, 25.7, 35.2, 44.8, 57.4 and 90.9 μm respectively. Corrections for the collection efficiencies of different drop diameters were made according to the theory of Langmuir and Blodgett (1946). The collection efficiencies were 43%, 73%, 85%, 93%, 98% and 100% for cloud drops of diameters 4 μm, 7 μm, 10 μm, 14 μm, 18 μm and >18 μm respectively at a true air speed of 54 m sec^{-1}.

3. Results and discussion

In this paper, cloud drop diameters are used and the heights are referred to msl. The mean cloud drop size spectra at different levels over the Arabian Sea and over the Pune region are presented in Figs. 1 and 2 respectively. The values of the cloud physical parameters are tabulated in Tables 1 and 2. The standard deviations are also shown in the figures and in the tables.

TABLE 1

Microphysical parameters for the clouds over the Arabian Sea

Height (above sea surface) (m)	No. of samples	LWC (g m^{-3})	N_T (cm^{-3})	N_L (cm^{-3})	MVD (μm)	DISP (μm μm^{-1})	Mode
640	5	.1112	212	.025	9.6	.51	B
		(.0895)	(146)	(.049)	(1.5)	(.11)	
870	12	.1585	186	.211	11.2	.59	B
		(.1072)	(83)	(.260)	(1.9)	(.13)	
980	8	.1721	181	.193	11.2	.58	B
		(.1192)	(52)	(.164)	(2.6)	(.17)	
1140	10	.1017	134	.012	10.3	.55	B
		(.0782)	(58)	(.037)	(2.3)	(.18)	
1420	7	.1217	98	.151	11.8	.57	B
		(.0973)	(43)	(.282)	(3.9)	(.16)	
1930	7	.2338	162	.357	13.0	.64	B
		(.2150)	(91)	(498)	(3.3)	(.14)	
			overall				
	49	.1498	161	.161	11.2	.57	B
		(.1304)	(88)	(.284)	(2.8)	(.15)	

LWC — Liquid water content, N_T — Total concentration of cloud drops,

N_L — Concentration of drops with diameter greater than 50 μm,

MVD — Mean volume diameter of drops, DISP — Dispersion, U — Unimodal,

B — Bimodal

Volume of cloud air sampled for each sample = 270 cm^3

Standard deviations are in brackets.

In Figs. 1, 2 and 3, the ordinate represents cloud drop number concentration per unit volume of cloud air per unit size interval. Further, in Figs. 1 and 2, the spectra for various heights have been displaced along the ordinate by one order, the displacement in the drop concentration being 10 times for each successive height.

3.1. *Variation with height over the Arabian Sea-Range of height : 640-1930 m above the sea surface*

The maximum size of the spectra ranged from 62 to 87 μm. The spectra broadened with height from 640 to 980 m, then narrowed up to 1420 m and then broadened again. The distributions were bimodal at all the levels, primary and secondary peak concentrations being at 7 and 30 μm, 7 and 62 μm, 7 and 48 μm, 7 and 45 μm, 7 and 30 μm, and 7 and 56 μm respectively at the respective increasing levels. The bimodal distribution suggests growth of some drops by coalescence. The said drop grew by collision coalescence of smaller drops to the size having the secondary peak concentration. N_T gradually decreased with height from 640 to 1420 m and increased at the highest level. It was maximum at the lowest level. The variation of N_L with height was irregular. It was maximum at the highest level and a minimum at 1140 m. The values of LWC, MVD and dispersion increased with height from 640 to 980 m, decreased at 1140 m and then increased again. They

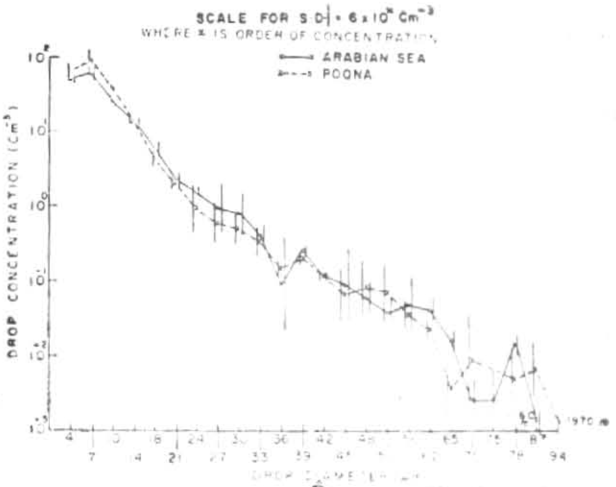

Fig. 3. Cloud drop size spectra over the Arabian Sea and Pune (Poona) for all the levels taken together

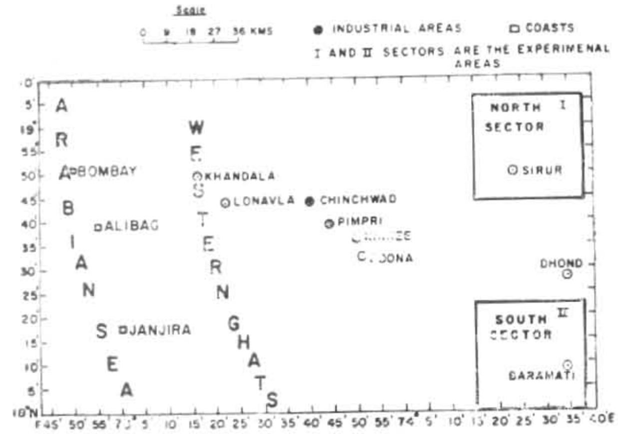

Fig. 4. Locations of the industrial and the experimental areas near Pune (Poona)

were maximum at the highest level. The values of MVD (mean 11.5 μm) at higher levels, 1140 m and upwards, were greater than those (mean 10.9 μm) at the lower levels (not statistically significant). The increase of the dispersion with height above cloud base is partly a reflection of the increase in frequency of bimodal distributions with height (Warner 1969).

3.2. *Variation with height over the Pune region-Range of height* : 1440-2610 *m above the mean sea level*

The maximum size of the spectra ranged from 33 to 94 μm. The spectra narrowed sharply at 1630 m with respect to the lowest level, broadened at 1880 m and then narrowed again. The distributions were bimodal at 1880 m and 2240 m, primary and secondary peaks being at 7 and 51 μm and at 7 and 48 μm at the respective levels. The distributions were unimodal at all other levels. N_T reduced sharply at 1630 m and 1880 m as compared to the lowermost level and thereafter increased falling a little at the top level. It was maximum at the lowest level. The variation of N_L with height was irregular. It was maximum at 2240 m and minimum at 1630 m. LWC decreased at 1630 m with respect to the lowest level and thereafter gradually increased, falling again at the highest level. MVD increased with height from 1440 m to 1880 m beyond which its variation was irregular. The values of MVD (mean 10.7 μm) at 2020 m and higher were slightly greater than those (mean 10.4 μm) at lower levels (not statistically significant). Dispersion decreased a little at 1630 m with respect to the lowest level, increased sharply at 1880 m, then reduced and remained nearly constant.

3.3. *Entrainment*

At 1630 m, over Pune, the values of maximum size N_L, LWC, N_T dispersion and concentration of 4 μm size drops were minimum out of all the levels. Similarly, at 1140 m and 1420 m, over the sea, the values of total drop concentrations, LWC, MVD and dispersion were lower with respect to the adjacent levels (980 m and 1930 m). The clouds might have been rising into relatively dry air above the boundary layer and thus they would have entrained dry air from the top and the sides. The mixing process might well evaporate some droplets more than others and a modified droplet spectrum would result (Telford *et al.* 1984). Further, the reductions in N_L, LWC, MVD, maximum size and concentrations of drops with diameters between 7 μm and 24 μm and above 42 μm at the highest level (2610 m) with respect to the adjacent lower level (2240 m), over Pune, suggest mixing of dry air from above the cloud top. The greater part of the dry air entrained into clouds enters the clouds from the dry air above the top (La Montagne and Telford 1983). It is the mixing at the growing cumulus cloud top as it builds that determines the shape of the droplet spectrum (Warner 1969). However, this discussion on entrainment is not very conclusive due to lack of sufficient data at adjacent layers and at the top of the clouds.

3.4. *Comparison of average spectra of the two regions*

The average spectra for the two places for all the levels taken together are shown in Fig. 3. The values of the average cloud physical parameters are given in Tables 1 and 2.

The average values of N_L, LWC, MVD and dispersion were slightly greater in the maritime clouds than those in the inland clouds. These differences were not statistically significant in the cases of N_L and LWC, nearly significant at 7.8% level for MVD and significant at 1.2% level for dispersion using the Wilcoxon-Mann-Whitney test. The maximum size (87 μm) over the sea was a little smaller than that (94 μm) over Pune. The average distribution over the sea was bimodal (primary and seecondary peaks at 7 μm and 78 μm respectively) while it was unimodal over Pune (peak at 7 μm). Average total concentration of drops over the sea was less than that over Pune significant at 5.6 % level. The mean concentrations of cloud drops of all sizes between 14 μm and 36 μm, *i.e.*, middle size drops (10.6 cm^{-3}, SD 12.0 cm^{-3}) for the maritime region were greater than those (7.9 cm^{-3}, SD 9.9 cm^{-3}) for the inland

TABLE 2

Microphysical parameters for the clouds over Pune (Details same as in Table 1)

Height (above mean sea level) (m)	No. of samples	LWC (gm^{-3})	N_T (cm^{-3})	N_L (cm^{-3})	MVD (μm)	DISP ($\mu m\ \mu m^{-1}$)	Mode
1440	7	.0962	284	0.44	8.5	.42	B
		(.0905)	(225)	(.108)	(1.8)	(.15)	
1630	10	.0617	138	0.0	9.7	.39	U
		(.0458)	(80)	—	(3.0)	(.13)	
1880	8	.1599	138	.223	13.2	.64	U
		(.0943)	(69)	(.187)	(3.2)	(.13)	
2020	10	.1747	223	.207	10.5	.54	U
		(.1980)	(140)	(.273)	(3.3)	(.14)	
2240	11	.1752	243	.266	11.1	.54	B
		(.0697)	(86)	(.177)	(1.0)	(.09)	
2610	4	.1365	236	.123	10.4	.55	U
		(.0610)	(105)	(.151)	(0.3)	(.09)	
Overall							
	50	.1358	206	.152	10.6	.51	U
		(.1194)	(136)	(.204)	(2.9)	(.15)	

Volume of cloud air sampled for each sample = 270 cm^3, Standard deviations are in brackets

region, being nearly significant at 9.5% level. The mean concentrations of both drops with diameters less than 14 μm (138 cm^{-3}, SD 72 cm^{-3}) and drops of size greater than 78 μm (0.0013 cm^{-3}, SD 0.0061 cm^{-3}) over the sea were smaller than those over Pune (185 cm^{-3}, SD 127 cm^{-3} and 0.0074 cm^{-3}, SD 0.0170 cm^{-3} respectively). The differences were significant at 3.2% level and 8.4% level respectively. The higher concentration of smaller size cloud drops over the inland region might be due to the presence of smaller size CCN particles (radius$\leq$1 μm) released into the atmosphere by combustion of wood and other fuels and by the smokes emanating from various factories. According to Hobbs and Radke (1970), the emission from chemical pulp and paper mills comprise of hygroscopic particles like Na_2SO_4, NH_4HSO_3, H_2SO_4 etc as well as free SO_2, and this emission and that from burning of wood waste are in the form of CCN particles with diameter from sub-micron to a few hundred microns. The higher concentration of largest size cloud drops (size greater than 78 μm) in the clouds over the Pune region might be due to the presence in air of some 'larger giant' CCN particles (radius much greater than 1 μm) derived from the effluents of mills near Pune. These particles in the modified maritime air grew by condensation/coalescence to drops bigger in size than the cloud drops in the purely maritime air. In this context, it may be noted that the experimental sites near Pune lie downward of an industrial complex belt containing paper mills, medicinal and chemical factories etc. Clouds that form in the effluent of a paper mill have a much broader spectrum of droplet sizes than those form in the unpolluted air (Eagan *et al.* 1974). The locations of the industrial and the experimental areas near Pune are shown in Fig. 4.

On an average, during the days of measurements, in the experimental area near Pune, the winds both at 0530 and 1730 IST were westerly at surface to 1.5 km (above surface) and southwesterly at 2.1 and 3.1 km. The average wind speeds at 0530 IST were 2.6, 7.2, 8.8, 7.3 and 5.1 m/s at surface, 0.9, 1.5, 2.1 and 3.1 km (above surface) respectively. Those at 1730 IST were 3.7, 7.8, 8.3, 6.4 and 5.1 m/s. Under the effect of the wind shears the effluents from the factories are dispersed properly and gradually mix up with the clouds in the experimental region, lying downwind.

4. Conclusion

The maximum size of the cloud droplet spectra increased with height for the Arabian Sea while those for Pune did not show a systematic change with height. However, the highest values of maximum size on both the locations, were observed midway between cloud top and cloud base. While comparing the two regions it may be noted here that the 'maximum size' depends upon the size of the samples. The drop size distributions over the sea were bimodal at all the levels while those over Pune were unimodal at most of the levels. Over the sea, total concentration of drops (N_T) decreased with height at all levels except at the highest level where it increased. Over Pune, the values of N_T decreased above the lowermost level and increased with altitude thereafter falling a little at the top level. N_T was highest at the lowest level at both the places. In both the locations, variation of N_L was irregular but its magnitude peaked near the top level. LWC, MVD and dispersion increased with height, in general, over the sea while their variations were irregular over Pune. The values of MVD at higher levels were greater and slightly greater than those at lowest levels over the maritime and inland locations respectively. Considering the over all spectra, the average values of N_L, LWC, MVD and dispersion were a little greater and total concentration smaller over the maritime than those over the inland region. The maximum size, concentration of drops of size less than 14 μm and concentration of drops of size greater than 78 μm were greater over Pune (modified maritime) than over the sea (maritime). Over both the locations, the cloud drops had tendency to grow in size with height, and this feature was more apparent for the maritime clouds than for the inland clouds.

References

Durbin, W. G., 1959, "Droplet sampling in cumulus clouds", *Tellus*, **11**, pp. 202-215.

Eagan, R.C., Hobbs, P.V. and Radke, L.F., 1974, "Particle emissions from a large kraft paper mill and their effects on the microstructure of warm clouds", *J. Appl. Met.*, **13**, pp. 535-552.

Hobbs, P.V. and Radke, L.F., 1970, "Cloud condensation nuclei from industrial sources and their apparent influence on precipitation in Washington State", *J. Atmos. Sci.*, **27**, pp. 81-89.

Jonas, P.R. and Mason, B.J., 1974, "The evolution of droplet spectra by condensation and coalescence in cumulus clouds", *Quart. J.R. Met. Soc.*, **100**, pp. 286-295.

La Montagne, R.G. and Telford, J.W., 1983, "Cloud top mixing in small cumuli", *J. Atmos. Sci.*, **40**, pp. 2148-2156.

Langmuir, I. and Blodgett, K.B., 1946, "A mathematical investigation of water droplet trajectories", U.S. Army Air Forces Tech. Rep. No 5418, Washington, D.C., 68 pp.

Silvermann, B.A. and Glass, M., 1973, "A numerical simulation of warm cumulus clouds : Part 1 — Parameterized *vs.* Non-parameterized microphysics", *J. Atmos. Sci.*, **30**, pp. 1620-1637.

Squires, P., 1958, "The microstructure and colloidal stability of warm clouds : Part 1—The relation between structure and stability", *Tellus*, **10**, pp. 256-261.

Srivastava, R.C. and Kapoor, R.K., 1960, "Drop size distribution and liquid water in a winter fog at Delhi", *Indian J. Met. Geophys.*, **11**, pp. 157-162.

Telford, J.W., Keck, T.S. and Chai, S.K., 1984, "Entrainment at cloud tops and the droplet spectra", *J. Atmos. Sci.*, **41**, pp. 3170-3179.

Warner, J., 1955, "The water content of cumuliform cloud", *Tellus*, **7**, pp. 449-457.

Warner, J., 1969, "The microstructure of cumulus cloud : Part 1— General features of the droplet spectrum", *J. Atmos. Sci.*, **26**, pp. 1049-1059.